Biologically Inspired 'Behavioral' Strategies for Autonomous Aerial Explorers on Mars

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Abstract – The natural world is a rich source of problem-solving approaches. This paper discusses the feasibility and technical challenges underlying mimicking, or analogously adapting, biological behavioral strategies to mission/flight planning for aerial vehicles engaged in planetary exploration. Two candidate concepts based on natural resource utilization and searching behaviors are adapted to technological applications. Prototypes and test missions addressing the difficulties of implementation and their solutions are also described.

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1. INTRODUCTION

A new aviation revolution is about to begin. Uninhabited aerial vehicles (UAVs) are finally reaching levels of technology maturation and mission capability that allow them to be applied to previously unachievable applications. 'Intelligent' UAVs -- whether used for terrestrial or planetary science applications – represent, perhaps, the ultimate autonomous system challenge. The development and use of aerial explorers to conduct robust planetary science missions -- for those planetary bodies which can support in-atmosphere flight – would provide a degree of mobility and access far above what could be achieved by any other means.

The "BEES for Mars" project is a NASA led research, development, and demonstration effort [1]. The goal of the "BEES for Mars" project can be stated as follows:

> ***Development of Bio-Inspired Flight Control Strategies to Enable Aerial Explorers for Mars Scientific Investigations***

Given this over-arching goal, the BEES for Mars (BfM) project currently can be summarized in terms of three general categories of research investigation: on-going funded work at University of California at Berkeley and Australian National University (ANU) on vision-based bio-inspired guidance, navigation, and control (GNC) systems; work being performed in-house at Ames Research Center on mission planning and execution software systems for aerial vehicles based on mimicking the search, find and foraging behaviors of various living creatures; and finally research focused around science field demonstrations using an assortment of aerial vehicles at Haughton Crater, Devon Island, in Nunavut, Canada, (a well-documented Mars-analog research site [2]).

A number of researchers have previously examined [3-4] the feasibility of mimicking biological behaviors in autonomous/robotic systems. The fundamental goal of this overall effort is to arrive at robust flight control systems that are computational efficient and can effect complex mission profiles in unknown environments, while being implemented on small, lightweight, and low power computer architectures. Only limited work to date has been focused on aerial vehicle flight control [3], all of which has been done for terrestrial UAVs and missions.

This paper discusses work in progress at NASA Ames Research Center addressing the feasibility of deriving innovative approaches to mission planning and execution for aerial explorers by mimicking -- or being inspired through analogy -- biological behaviors.

2. OBJECTIVES FOR MISSION DESIGN

There are several unique mission requirements, above and beyond that of terrestrial UAVs, which support the

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application of bio-inspired flight/mission control strategies to general classes of possible aerial explorers for Mars exploration. Foremost among these is that a fundamentally different "search and find" philosophy exists for planetary exploration versus terrestrial aerial surveys.

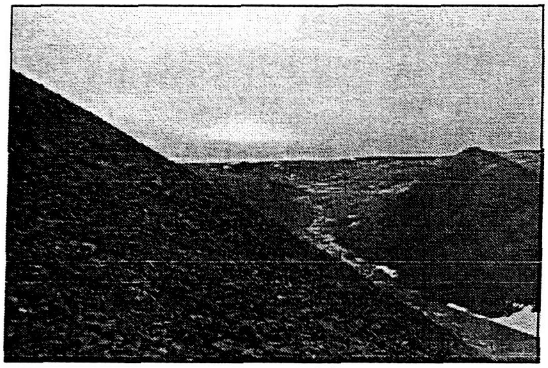
Mars Versus Earth

As noted earlier, though there are common technical challenges for uninhabited aerial vehicles for terrestrial versus planetary applications, there are several noteworthy differences as well. Some of these similarities and differences are summarized in Table 1.

Table 1. Comparison of Mars and Earth UAV Surveys

Criteria	Mars	Earth
Atmospheric Surface Pressure	6-10 mBar	1 Bar
Gravity	0.371G	1 G (9.81 m/sec^2)
Mean Surface Atmospheric Temperatures	214 Degrees. Kelvin	STP (Standard Temperature Pressure at Sea Level): 293 Degrees. Kelvin
Mean Surface Atmospheric Density	1.55x10^{-2} kg/m^3	1.23 kg/m^3
Primary Atmospheric Constituents	CO_2 95%, N_2 2.7%, Ar 1.6%, & O_2 0.1%	N_2 78% & O_2 21%
Flight Speed	-Fixed-wing aircraft will have to fly at very high speeds, near transonic flow conditions, to have adequate lift - Imaging from fixed-wing aircraft will have to require high frame rates to minimize blurring - Developing ultra-lightweight structures for Mars aircraft flying at transonic speeds presents unique challenges	- Low-speed subsonic flight can be sustained for fixed-wing aircraft - Imaging from a low-speed terrestrial fixed-wing aircraft will be considerably different, and less daunting than on Mars - Aircraft design weight targets are less strenuous than for a Mars flyer
Stowage, Transport, & Deployment	-These issues dominate the development of Mars flyers -Development of mechanical/structural concepts that yield a small stowed package in current EDLS designs, but deploy as an aerodynamically efficient flyer upon arrival at Mars is still a major line of research investigation	-Generally these issues are not a primary design constraints for terrestrial aircraft
Propulsion	- Mars has insufficient oxygen in its atmosphere for conventional propulsion systems - Considerable research effort is needed to develop robust, efficient propulsion systems having the power/energy densities needed for Mars flyers	Closest terrestrial analogs are high altitude (< 80K ft.) aircraft.
Infrastructure	- No runways, ground-handling crews, and maintenance exist on Mars; alternate approaches to providing this kind of support will be required - Providing high bandwidth real-time telecom for aerial flyers will be a significant challenge; no global satellite coverage, and no ionosphere off of which to bounce long-distance radio signals.	- Even the most automated of current terrestrial UAVs has a substantial support crew of human operators and technicians to fly and maintain the aircraft for multiple missions/flights - With the available world-wide satellite coverage; telecom is not a major issue for terrestrial UAVs
Navigation	- No GPS. Primarily use of vision systems. - No Mars magnetic poles and, therefore, no compasses - Global maps of Mars are far less detailed than equivalent maps of Earth - Navigation will tend to use more 'relational' than absolute coordinates	- GPS-dominated strategies - Absolute coordinates will be used more than 'relational' ones
Autonomy	High-level autonomy with no real-time in-flight interaction with Earth	Scaleable autonomy with significant "man-in-loop" interaction

It is crucial to insure that any terrestrial demonstrations of bio-inspired flight control technologies at Mars-analog sites, such as Haughton Crater (Figure 1 a-c), are truly representative of the conditions and constraints of a Mars mission. This is not an easy challenge. A considerable amount of discussion in this paper is devoted not only to the bio-inspired behavioral flight control modeling, but to the technology demonstration inherent in this work.



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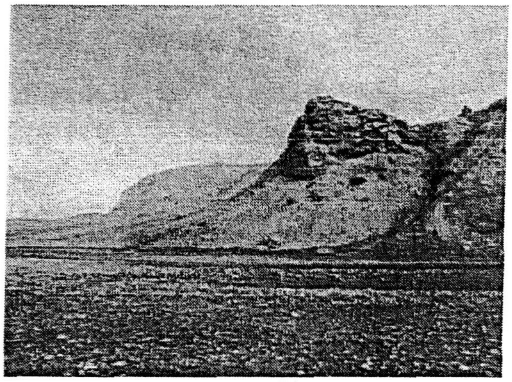

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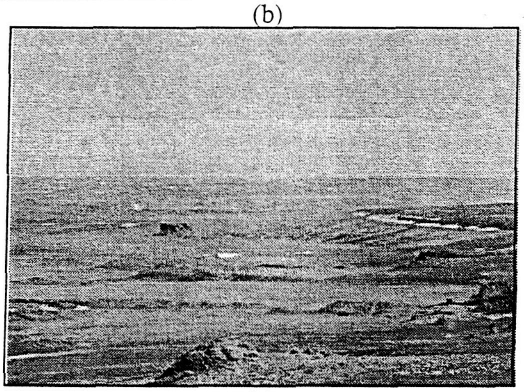

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Figure 1a-c – Ground Images of the Haughton Crater, Devon Island (Mars-Analog Site).

Autonomy

Human presence is not yet available for planetary surface exploration. At present, Mars vehicles are tele-operated from Earth, a practice which makes inefficient use of a vehicle's operational lifetime and is cumbersome in terms of logistics and use of the expensive resource of researchers' time. While the time delay for transmissions to Mars is only a few minutes, planetary rotation and the human decision-making process result in a typical rate of one command per solar cycle.

Autonomy technology offers the potential advantages of increased efficiency in resource utilization, greater science return on exploration missions, and the possibility for spin-offs to other applications of autonomy. Ongoing research at Ames addresses the development of autonomous vehicles for planetary surface exploration.

Search-related Operations

Remote exploration applications such as Mars missions offer an opportunity for innovation in how we use machines. The use of tools, even highly complex ones, is a familiar human behavior. With automation, we are accustomed to having machines assume control of repetitive or highly structured tasks.

With autonomous vehicles, it is tempting to program decision-making algorithms to mimic our own analytical processes, or to regard autonomy as the next step up in sophistication from automation. Both cases represent the significant challenge of capturing complex human reasoning and procedures.

Biologically-inspired mission design focuses on a simplified operational purpose. Mars exploration missions have the general goal of seeking data in support of scientific investigations. By turning to search-related behaviors in nature, we introduce a source of mission design which is not derived from human behaviors or history with machines.

3. Biologically-inspired Mission Concepts

Candidate Aerial Explorer Missions

In order to map, through analogy, biological behaviors to engineering applications, it is necessary to first identify general classes of aerial vehicles and mission concepts for Mars exploration. Further, these general classes of vehicles and mission concepts must address Mars exploration program goals and objectives [5] in order to be successful.

The literature is full of examples of aerial vehicle concepts for Mars (and other planetary body) exploration: balloons/aerostats [6]; airships [7-8]; subsonic fixed wing airplanes [9-10]; hypersonic hybrid entry-vehicles/aircraft; ballistic 'hoppers' [11-13]; flapping-wing 'ornithopters' [14]; and vertical lift, rotary-wing vehicles [15-28]. From this large set of vehicle concepts a limited number of general classes of aerial explorer types and mission concepts will be identified. An appropriate matching set of search and find, or rather foraging, behaviors from biology will then be identified and shown to be applicable, in an analogous sense, to the planning and execution of aerial explorer missions.

Table 2. General Classes of Aerial Explorers and Missions

General Class of Aerial Exploration Mission	Types of Applicable Aircraft Configurations	Mission & Vehicle Characteristics	MEPAG Goals & Objectives Addressed
High Altitude and/or Long Endurance	- Balloons - Supersonic, or hypersonic, rocket-powered fixed-wing, or lifting-body, aircraft	- Large survey area (medium resolution) mapping - Atmospheric chemical and particulate constituent sampling - Atmospheric turbulence, transport mechanisms, and overall meteorological measurements	
Medium Altitude and Endurance	- Balloons and/or Airships - Fixed-Wing (Transonic, or high-speed Subsonic) Airplanes (either EDLS air-deployed or surface rocket-launched) - Gliders - Steerable auto-gyro entry pod - Steerable parachute entry pod	- Medium survey area (medium resolution) mapping/imaging - Mapping mission could be precursor for large rover mission - Transport & release of science pods - Imaging primarily would support geological and climatology investigations - Focus on observing water erosion features on the surface	
Low Altitude, Low Speed, With Surface Interaction	- Rotorcraft and/or other vertical lift aerial vehicles - Ballistic hoppers (chemical & mechanical) - Ornithopters - Aerostats	- In-flight ability to acquire high resolution aerial survey images from a unique low-altitude vantage point - If vehicle has ability to soft-land and take-off then ground-level panoramic images can provide "ground truth" to aerial survey images; otherwise, aerial vehicle may drop imaging pods to the ground providing similar information - Soil and rock sampling performed by an aerial vehicle that soft lands and takes off; specimens are analyzed onboard the aerial vehicle or (to minimize the gross weight of the vehicle) be returned and analyzed at a lander, or rover (for very small aerial vehicles), "home base"	1. MEPAG Goal I, Objective A, "Determine if Life Exists Today," Investigation 2, 3.,5, 6 2. Goal I, Obj. B, "Determine if Life Existed in the Past," Investig. 1 & 2 3. Goal I, Obj. C, "Assess Pre-Biotic Organic Chemistry," Investig. 1 4. Goal III, Obj. A, "Determine Present State, Distribution, and Cycling of Water," Investig. 2

For almost all of the above general classes of aerial explorers, there are several common elements between the mission and flight characteristics (Table 2) for these aerial vehicles, as well as similar mission requirements (Table 1). For the purposes for this paper these can be distilled to four technical elements (which will be studied in detail in this paper): the need for a robust imaging/vision system for both navigation and scientific data; mission planning software that is efficiently tailored for searching and finding scientifically interesting surface features; the need to establish "ground truth" for calibration/correlation with the aerial vehicle survey results; and, finally, the use of three-dimensional mobility to maximize science return, and allow for flexibility to capitalize on serendipitous discoveries.

Inspiration from Biology and Application to Engineering

Classic Mission Planners versus Bio-Inspired Behaviors – Flight control and navigation models will be quite different between terrestrial UAVs and planetary aerial vehicles. This will include different engineering approaches with regards to: relational versus absolute coordinates, flight pattern search and find (grid patterns versus random walk, dispersal, and/or 'tracking') strategies.

Biological Models – Research on biological models [3] suggests that living creatures evolve their search and find behaviors to maximize E/T, i.e. the energy intake per unit of time foraging. Making efficient use of time is a strategy familiar to humans; human behavior intended to maximize the use of time often involves hurrying. Plants and animals don't commonly hurry. Their strategies and activities are strongly driven by E_{in}/E_{out}, i.e., energy gained relative to energy expended. While extreme energy expenditures such as fleeing and chasing can be effective when warranted, hurrying behaviors are usually kept to a minimum as they are not efficient behaviors for foraging (Figure 2).

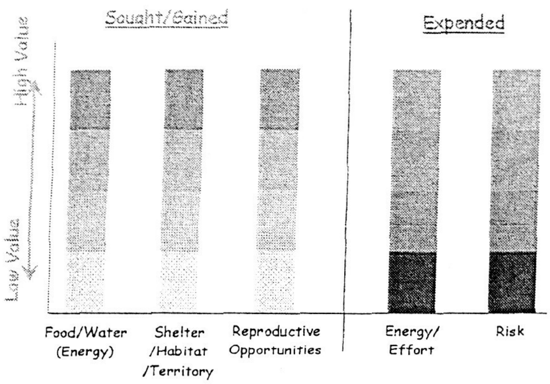


Figure 2 - Biological Energy Model

In seeking inspiration from biology for application to engineering, initially a wide variety of living creature behavioral models, and modeling issues, were considered for a range of exploration missions. Among the bio-inspired models/issues considered were:

- Resource utilization in the r and K selection strategies of survivorship curves. Habitat selection by biological organisms offered bio-inspiration for site selection in remote exploration missions.
- Landscape tracking as typified by the example of a fox hunting mice. Awareness of the environment (habitat) provides cues for determining a promising search path.
- Cooperation as illustrated by the Information Center Hypothesis (ICH) [29] and wolf pack territory utilization strategies. Examples of birds and wolves making choices in how to search an area for food can apply to optimizing autonomous vehicles in search of data.
- Community as perhaps best exemplified by Charles Darwin's "Economy of Nature." The concept of energy and material exchanged among species in a community could be modified to such a thing as an information ecosystem defined in the context of cooperating robotic systems engaged in planetary science missions.
- Using the characteristics of our biosphere and the philosophical question, "What is life?" to seek evidence of life on Mars. Many exploration missions seeking evidence of a biological presence on Mars would be satisfied to find a single organism. Life as we know it is not isolated and static but widespread, diverse, and exhibits dynamic equilibrium.
- And finally, is there a role for mobile robotic exploration systems employing non-deterministic trajectories, such as that evidenced by tumbleweeds, for example balloon robotics that might rise in the day and land at night [30]. Following terrain gradients and wind forces may be appropriate for some types of long-term data collection.

After considering many of these modeling issues/considerations, the BEES for Mars project research was distilled down to two general strategies most applicable to search and find missions. There are numerous opportunities to consider other scenarios and biological behavioral models for application to missions with other goals or scientific hypotheses.

There is significant inspiration for biological models (both cooperative and individual organisms) for foraging and search and find behaviors that might be mimicked by aerial vehicle flight/mission planning control architectures (Table 3). Foraging and seeking behaviors most closely parallel the requirements of remote exploration missions by autonomous vehicles. Cooperation or other multi-robot interactions will be another important area of research.

Table 3 - Biological Models and Associated Search and Find, or Foraging Behaviors

Biological Model	Class of Behavior	Behavior
E. Coli Bacteria	Foraging	Random walk movement
Moths	Reproduction/ Seeking Mate	Following a chemical gradient indicating increasing presence of resource
Birds	Communal foraging	Following a competitor to locate a resource
Ants	Trail -following	Following a chemical trail to locate a resource
Bees	Communication	Following directions to locate a resource
Sharks, Bats	Hunting	Finding prey through non-visual cues
Foxes, Wolves	Landscape tracking	Environmentally determined search path

Figure 3 – A Hierarchy of Cooperative and Individual Biological Models for Engineering Inspiration

A considerable amount of work is repeated in the literature regarding cooperative robotics [31]. Many concepts for cooperative robotic autonomy are based on modeling engineering systems after swarms of insects emulating their population level of organization. It should be noted though that community level interactions do not require separate cooperative functions. Each member's function complements other functions. Basic ecological roles in a community – producers, consumers, decomposers – focus on energy and matter. The commodities exchanged in robotic exploration are energy and information.

Though some benefit can be derived from review of such intelligent systems concepts of 'robotic colonies,' Mars exploration missions will likely only entail a limited number of sustained robotic systems on the planet at one time. Hence, the primary focus of the BEES for Mars project will be on individual living creature search and find, or foraging, behavioral models. But, even with two to three co-existent robotic systems, there can be a substantial opportunity to embody/mimic cooperation (Figure 3). Such robotic systems, even of two to three distinct systems, can be thought of as producers, consumers, and decomposers of information when considered in the context of planetary science investigations (Figure.4). The following examples are offered: (1) Power Generation systems: performed by energy station; receives solar energy, commands; produces power; (2) Data collection systems: performed by rover(s) and/or aerial vehicles; receives battery power and commands; produces data; (3) Command & control systems: performed by autonomous 'reasoner;' receives data and power, producing decisions and conclusions.

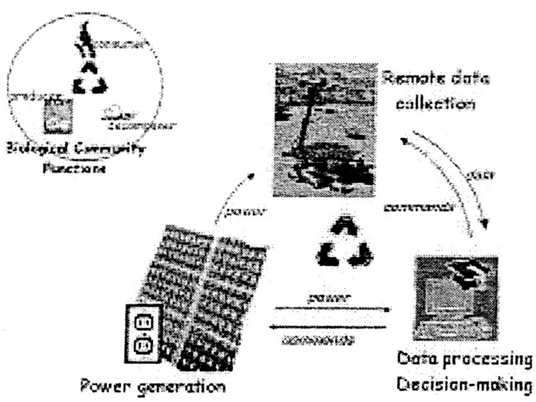


Figure 4 – Producers, Consumers, and Decomposers: Biology versus Planetary Exploration

The work reported in this paper will focus on the two primary exploration scenarios and types of aerial explorer behavioral models: the "r & K" and the "Fox and Mouse" strategies (Figures 5 and 6).

Background on Biological Inspiration

The following development path is currently being pursued by NASA Ames with respect to the demonstration of bio-inspired flight behaviors.

Scenario 1. r & K Strategy. – The r & K mission concept takes two ends of a continuum of biological reproductive strategies and applies them to exploration. The letters r and K are variables in widely used equations for modeling populations, where r is rate of population growth and K is maximum sustainable population [32, 33]. Survival and reproductive strategies in nature are innumerable. Simply put, the r-selection approach is typically found in species whose unstable environments cause them to adopt a strategy seeking to maximize population growth, while the K-selection approach applies to more resource-limited situations requiring care and protection in the face of competition.

For our purposes, the r-selection strategy describes the random, widespread dissemination of organisms with a short lifespan in the hope that some will survive and disperse. Examples in plants and animals might be dandelion seeds, abalone, and rabbits. The K-selection strategy describes the development and delivery of relatively few offspring with greater investment of energy such as walnuts, elephants, or hummingbirds (Figure 5).

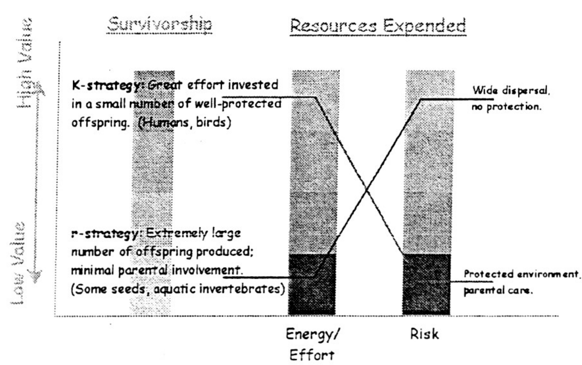


Figure 5 - r & K scenario logic

The emulation of the r & K strategy in aerial explorers leverages the advantages of each strategy to allow for a more efficient aerial search by the Mars flyers. The following description is for the r and K strategy applied to a Mars search scenario (Figures 6 a, b).

A number of low cost, simple pods are distributed over a wide area by an autonomous UAV (perhaps a medium altitude and medium range fixed wing UAV). The data from the pods are collected and used to develop a utility value (level of interest) for each location or general area. This utility, along with UAV performance and limitations, is then used to develop a plan that prioritizes sites of interest for visitation. Another, follow-on autonomous vehicle (such as an autonomous rotorcraft, rover, or ballistic hopper) uses this plan to deliver a more capable sensor package to the specific sites to perform more extensive analysis.

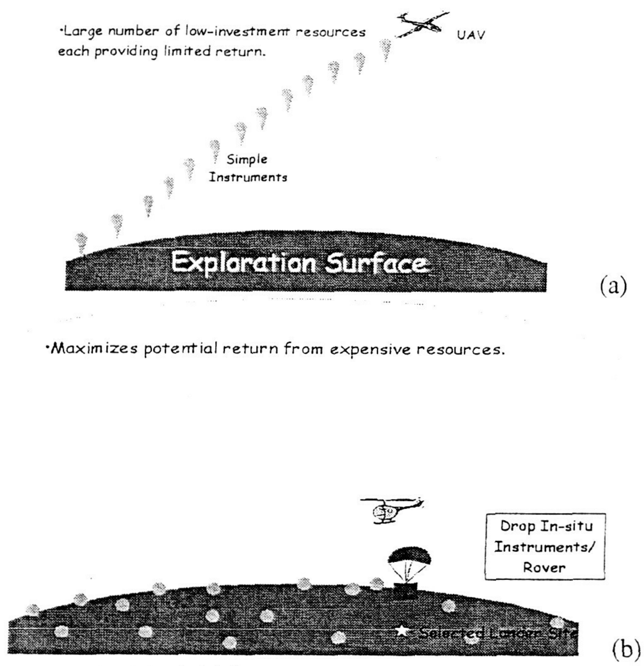


Figure 6 – (a) r initial strategy and (b) K follow-up strategy as envisioned for aerial explorers

In addition to placing sensors, the UAV could also return local video/images of the area resulting in a calibration of aerial survey images from Mars flyers with ground truth images from installed cameras in the drop pods.

Scenario 2. Fox and Mouse Strategy – The Fox and Mouse strategy uses the experience and intelligence applied by the Fox in searching for its potential prey, the Mouse. Mice use vegetation cover for protection but must often forage in more open areas. Foxes and other similar animals focus their search for prey along the transition line between the cover and the open. The fox knows from experience that it will have only a slight chance of locating its prey in the open space that borders the covering bush. It also knows that the vegetated area is where the mice can more easily be found, but are also more difficult to catch among the bushes and brambles. The fox therefore, optimizes its use of energy by hunting along the edge line, or ecotone, between the bush and the open, which gives it the best possibility of seeing mice and also presents the best probability of catching them.

Project managers and scientists have necessarily different and competing goals in achieving a Mars exploration mission. The project managers want to land a rover in a place with the least amount of risk to the lander: an area where there is the least amount of rocks or large boulders. On the other hand, the scientist wants to be as close to the rocky outcroppings, water flow outwash, and cliff striations and ledges as possible. Rugged terrain is where the information needed to support or reject many hypotheses related to geologic history is located.

The following is an example of how the Fox and Mouse strategy could be applied to Mars exploration (Figure 7). An autonomous UAV is used as an advanced scout to search out and find the transition area between the flat plains (field) and the rocky slopes (brambles). The UAV identifies these areas by using an altitude sensor to map the slope of the area.

The UAV then uses on-board sensors to search for geographic forms (gullies, dry riverbeds, striated rocks) in the transition zone. These forms would likely lead the UAV to rocks that are rich in carbonates and other minerals that would indicate signs of water.

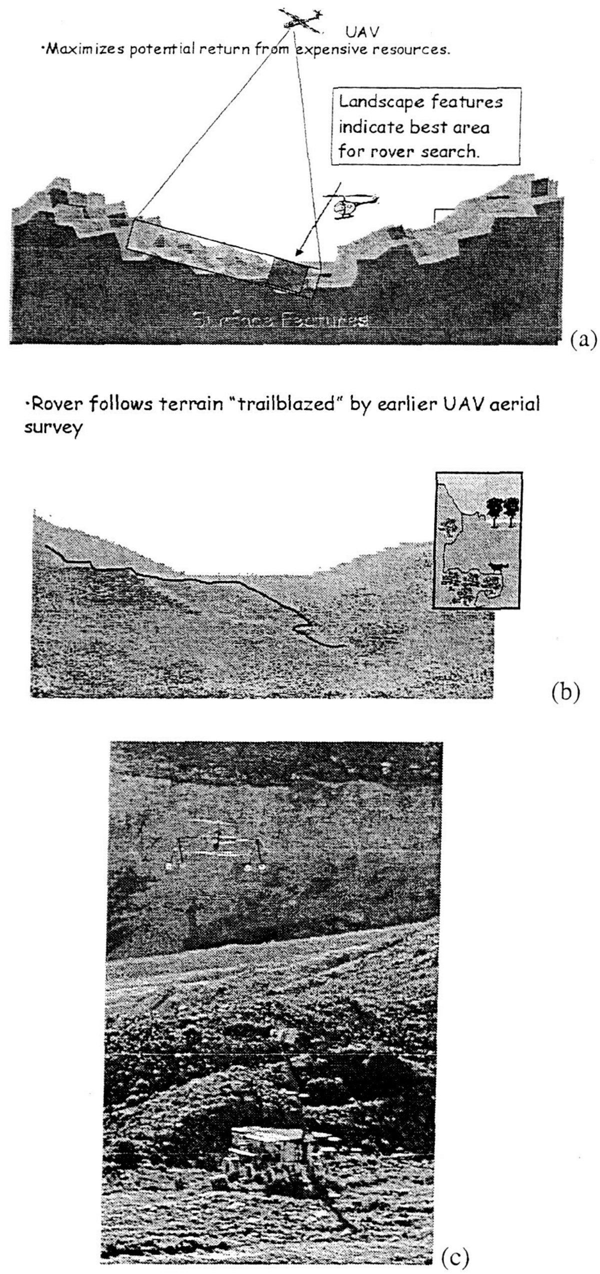


Figure 7 – "Fox and Mouse" Strategy as Applied to Aerial Explorers Searching for High Value Geological and Astrobiological Features of Interest

The transition zone, local slopes, paths found, and identified materials could later be used by mission managers and scientists to plan the landing, transition, and best path to an interesting area that would likely provide the highest science return for the lowest project risk.

4. ENGINEERING DESIGN AND IMPLEMENTATION

Simulation and Demonstration

A two-pronged technical approach will be taken to establish the feasibility of developing and using bio-inspired behaviors in aerial vehicle flight. The first goal will be to establish a simulation environment in which to develop and test the autonomous algorithms. This will be accomplished by using existing simulation tools and flight test assets available at NASA Ames (for example, the Mission Simulation Facility [34], Riptide [35]) and/or by integrating commercially available software. It is hoped that many of the same resources can also be used to develop a ground system, where the autonomy and flight plans can be rehearsed as well as monitored and observed. The simulation environment will have the capability of simulating the flight of the aircraft and sensor input as well as terrain and targets in subject areas.

The bio-inspired algorithms will be developed using an architecture and autonomy software that will be capable of running within a Linux platform. Using a standard Linux platform should provide access to many of the autonomy and sensor software developed by third-party research groups and universities.

Current work is focused on developing or adapting an architecture that will allow different software modules and sensors to be used by the system. Among several being evaluated is an architecture being developed for the Autonomous Rotorcraft project at Ames [36]. An initial essential module may be an adaptation of a Conditional Executive [37] for use to control the decision-making on the UAV.

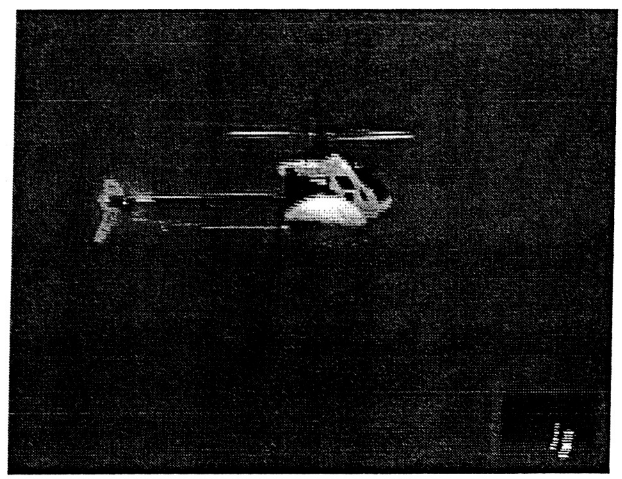
The second goal, in parallel with algorithm development, will be to modestly expand the capabilities of the UAV test platform. The processing power of the UAV will be enhanced by fully integrating a Linux PC 104 or similar processing system into the aircraft. This onboard system will be capable of autonomously controlling the flight of the aircraft by accessing a command library to the flight processor. A second wireless modem will allow access to other ground based autonomous systems (for example, a planner or database) providing better monitoring of the operation of this system.

As the autonomy algorithms mature in simulation, individual modules and routines will be tested on the flight hardware. If possible, algorithms will run on the target processor integrated with the simulation system ("hardware in the loop"), allowing the initial testing of the hardware and software on the ground using simulated sensor inputs. The algorithms will then be tested in flight, first in isolated module tests, and then integrated into more extensive flight demonstrations.

As tests are successful completed at the local test site (Moffett Field), tests will then be performed at a "Haughton Crater Analog" site, probably Camp Roberts in Central California. This site provides a more extensive area in which to fly and will also provides hills and valleys to test the operational and technical capabilities of the system and flight team.

Utility of Prototyping

A number of hardware and software prototyping efforts are currently underway at NASA Ames. Figures 8 and 9 show some early efforts to drop/release science pods and smaller flyers from 'mothership' flight platform.



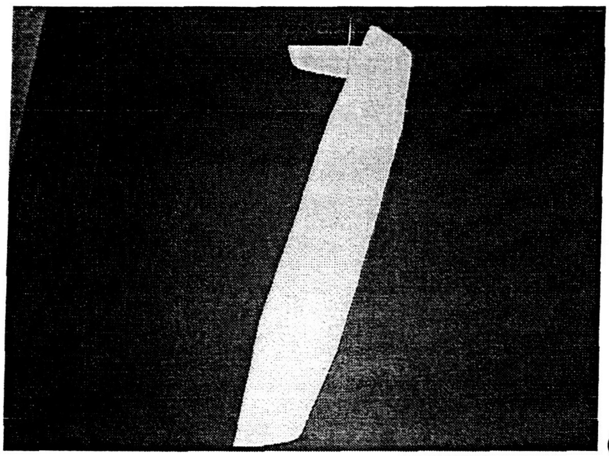
(a)

(b)

Figure 8 --Dissemination/Distribution (a) 'mothership' carrying pod, (b) pod release from 'mothership'.

Figure 8 shows a video camera embedded in an impact-resistant pod that is released from the radio-controlled helicopter. The images gathered from the video camera during descent and while on the ground can be 'calibrated' against images from the mothership at cruise altitude. This would then allow images taken at cruise altitude to be interpreted in light of pod images to give a grounds-eye view, given a limited number of these single-sample data points represented by pods being released in-flight. This early attempt at the release of imaging drop pods from an aerial vehicle is currently being followed up by more rigorous examination of the drop pod concept with fixed-wing flyers.

Figure 9 shows a small oblique wing glider being developed for launch in a coordinated group of aerial flyers from a mothership, in this case a large radio-controlled helicopter. This aerial release of small gliders is a first-order simulation of the mid-air deployment of small flyers from an EDLS (Entry, Descent, Landing System).



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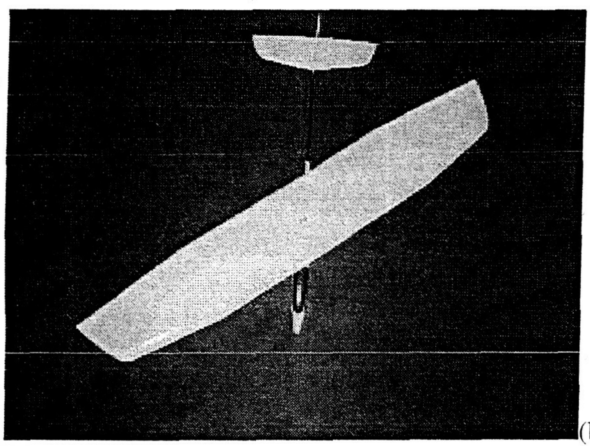

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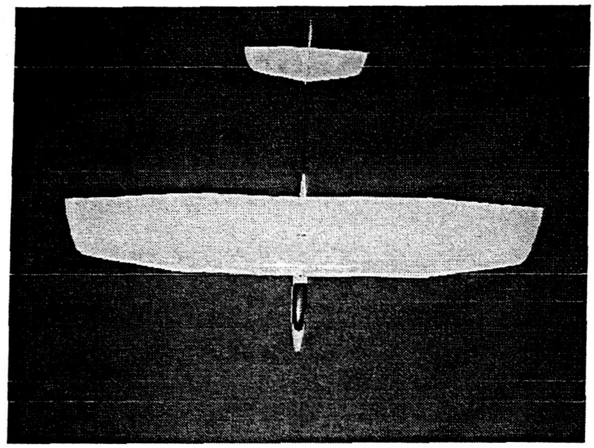
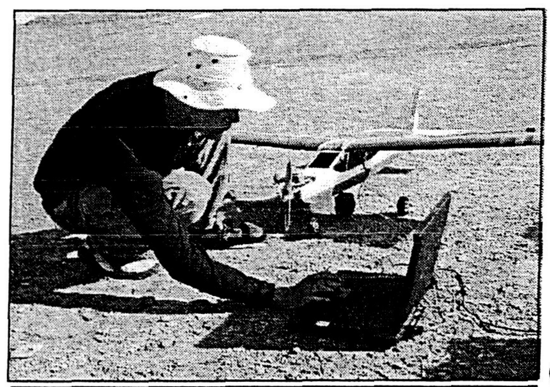


(c)

Figure 9 -- Symbiosis: release of gliders from 'mothership' (a) stowed configuration, (b) wing pivoting upon release, and (c) glider in level-flight configuration.

An initial demonstration of aerial explorer flight at Haughton Crater was conducted in the summer of 2002. A small commercial UAV was taken to the Mars-analog site and flown over a number of geologically interesting stretches of terrain (Figure 10). The UAV was capable of being line-of-sight radio-controlled from the ground and flown through pre-programmed GPS waypoints. This initial demonstration was primarily for site familiarization purposes as well as acquiring imaging data to enable the development of vision-based navigation systems. Follow-on demonstrations in the summers of 2003 and 2004 are currently planned. Information acquired during the summer 2002 site visit will enable the definition of controlled, robust, field demonstrations in the following years.



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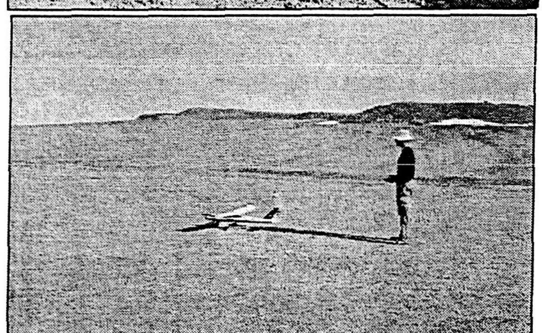

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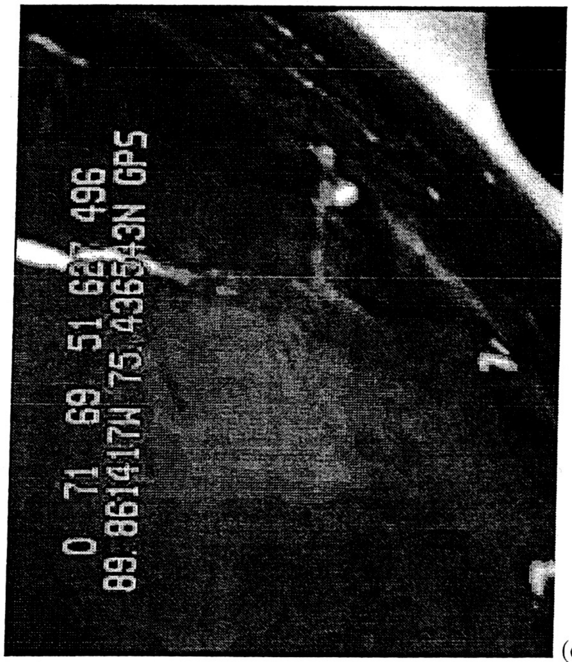


(c)

Figure 10 – Summer Field Demo 2002 (a) aerial flyer pre-flight, (b) take-off, and (c) in-flight wireless video.

5. CASE STUDY: FROM OBSERVED BIOLOGICAL BEHAVIORS TO MISSION PLANNING

An initial baseline mission has been identified for the 'BEES for Mars' project to demonstrate the feasibility of biological behavior modeling as applied to aerial flyer mission planning and execution. Upon successful demonstration of this baseline mission profile, significantly more sophisticated mission profiles will be simulated in Mars-analog sites as a part of the overall 'BEES for Mars' project. Figure 11 schematically shows the flight profile of this baseline mission.

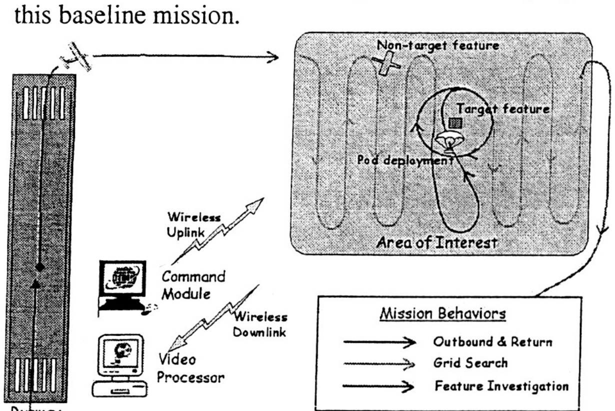


Figure 11– Schematic of 10/02 Baseline Flight Demo

In October 2002, a fully autonomous flight demonstration of mapping and recognition behaviors was demonstrated by a team consisting of the QSS Group and the MLB Company at Moffett Field, CA. The flight system for this demonstration involved a MLB Bat UAV with a video downlink, a two-way modem communication system, and ground station capable of reprogramming the aircraft in flight. MLB also developed a video drop pod with parachute, deployment mechanism, and video system that could provide real time transmission of video from the pod.

A video recognition system was developed at QSS that was capable of being tuned to recognize the color and shape of simple objects. Using video recorded from the UAV, this system was first tuned in the lab to recognize a 12 foot orange square from the UAV nominal cruising altitude (400 ft). Upon recognition, this system sent a message indicating the presence of the orange square and its position in the video frame.

The UAV programming and route were first tested at Moffett Field using a human to recognize and indicate the position of the orange square from the ground station. During a subsequent test, the recognition software was integrated into the ground system and the color level and recognition point was adjusted.

The autonomous flight plan was as follows: The aircraft performed an autonomous takeoff and transition behavior to an area of interest. It then commenced an overlapping mapping behavior to return video images to the base station and to look for the target. Upon receiving the "found" message from the recognition software, the ground system sent an updated plan to the aircraft instructing it to fly back to the recognition point, deploy the pod, then fly a ¼ mile circling pattern, keeping the position of the square in view. Once this discovery/examination behavior was complete, the UAV resumed its search pattern until the area of interest was completely searched, then the aircraft flew back to the departure point and landed autonomously. Figures 12a-e show the drop pod and video images from this successful flight test and demonstration.

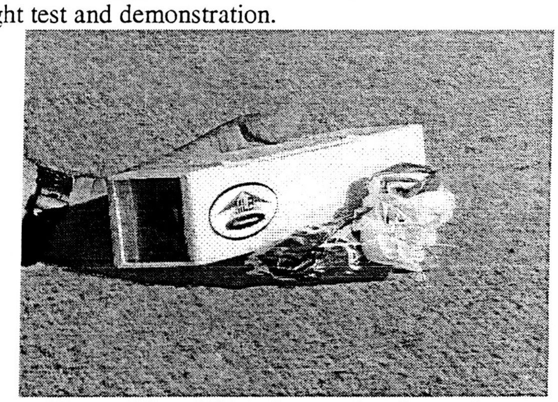


Figure 12a – Video drop pod and parachute

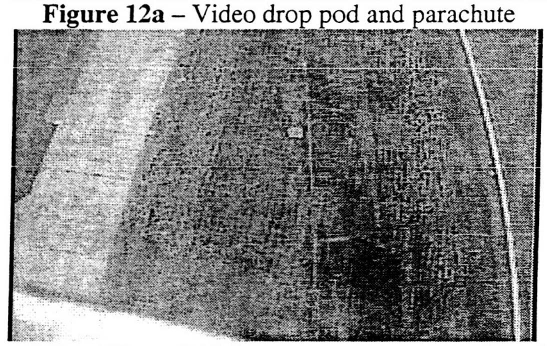


Figure 12b – View of 12 ft square orange target from UAV at recognition.

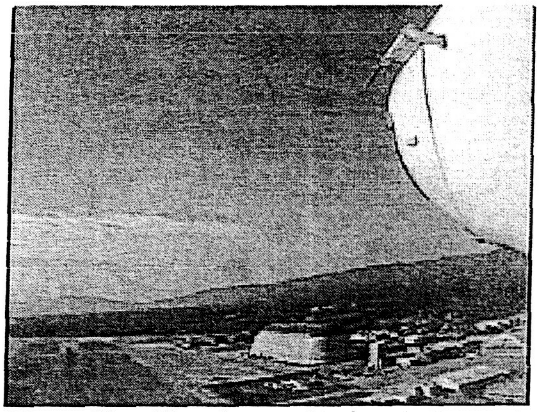


Figure 12c - View from pod before deployment

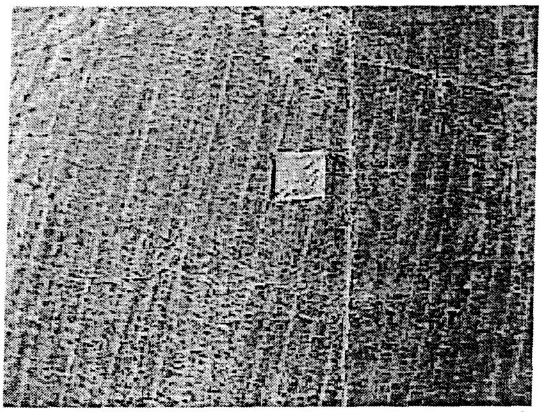


Figure 12d – Real time view from pod of target after deployment

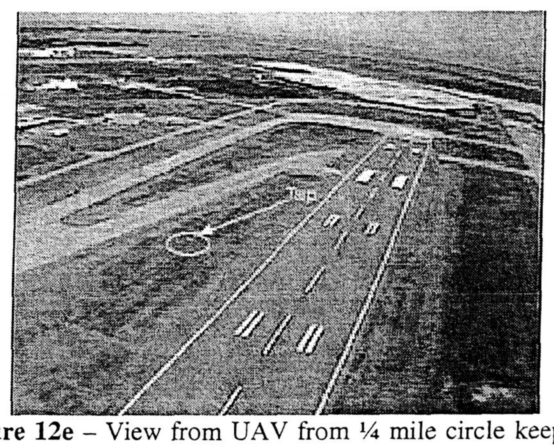
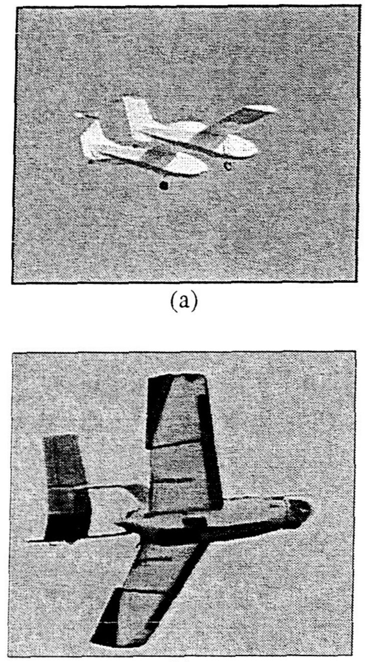


Figure 12e – View from UAV from ¼ mile circle keeping the target position in view

6. FUTURE PLAN(E)S

The work discussed in this paper is intended to directly contribute to field demonstrations of a variety of bio-inspired technologies, on small aerial flyers, for the 'BEES for Mars' project at a Mars-analog site in the Summer of 2003 and 2004. Besides the small aerial flyer shown in Figure 10 (used for the initial feasibility studies), additional small UAVs might be used in the 'BEES for Mars' demonstrations (Figure 13 a, b).



(a)

(b)

Figure 13 - (a) ACAT and (b) MLB 'Bat' Flyers

Actions, Observations, and Decision-making

The focus of the work reported in this paper is on bio-inspired UAV behaviors in the form of actions (tasks), and observations (data sensing). Nonetheless, a parallel line of information technology research investigation can and should be ultimately coupled to the bio-inspired behaviors work detailed in this paper: the burgeoning field of evolutionary programming and behavioral modeling [38-40]. This is a missing essential element for a complete bio-inspired intelligent aerial vehicle solution.

Autonomous UAVs are currently programmed by humans, using standard programming structures, architectures and concepts. The Meta code listing in Table 5 is an example of behaviors and sensing applied in this manner. In this method, the actions and decisions are chosen by the programmer. Given a stimulus (seeing a red tarp) the UAV should react predictably to drop a probe or do a different action (based on the reliability and resolution of the sensors and hardware). The resulting system can be exhaustively tested in the lab and in flight and improved. In summary, a human selected the behaviors in advance, based on his or her understanding of the success of the behaviors in that environment or situation.

We have established that UAVs can exhibit many biologically inspired behaviors, both at the mission and the planning level. There may or may not be a need or desire for that UAV to behave like a single animal (for example, a fox) at any time to accomplish a task. Our belief is that a biologically inspired UAV could and should mix or choose the behaviors that solve the task. In order to efficiently find and understand strategies beyond what a human may choose, these successful behaviors will need to be experimented with by the UAV through training and learning.

Neural nets have been successfully used to "train" a system to recognize certain input and react in predictable ways [41]. It is possible that UAVs could be more efficiently programmed to perform some reactionary tasks (such as following an altitude gradient, or reacting quickly to a strong down draft) using Neural Net techniques.

The use of Genetic algorithms [38] are techniques that can be used to develop new and more efficient behaviors based on the information sensed within an environment. Using genetic programming, an UAV is set within a simulated environment with specific tasks that would need to be completed. For example, the UAV could be tasked search for a landmark within an area with a given wind and visibility. The UAV has free reign to choose any sensor, behavior, time, or configuration to achieve that task. Using Monte Carlo techniques, UAVs given different choices would be evaluated on the success of their mission. Over successive generations, several leading "behaviors" would emerge, most of which might not be readily apparent when first approaching the problem. These behaviors could be evaluated in the field and eventually integrated into the aircraft's decision and action plans.

Finally, at an overarching level, behavioral modeling could be used to provide the architecture in which autonomous decisions and actions are represented and executed by the UAV. Biological entities such as Animals and Man can be described as organisms that operate under a simple Behavioral Model [39, 40]: Organisms are *Motivated* to do *Actions*, because of the changing state of their *Emotions* and what they *Sense* in the world.

In this architecture, the UAV would be provided many different actions (or sequence of actions) that could be selected and executed at any time. Actions could be reactionary (quick) or deliberative based on the current motivations.

The goals of the system would be represented as motivations. Motivations could include mission goals (find the object) or internal goals (avoid collisions with mountains). Many motivations may be active at any time and would be ranked by importance at any time by an Emotion model. Important motivations would be the ones that would be active at any time and the system would be free to choose from several actions in order to achieve a goal.

The Emotional model would perceive the world via the sensors and would maintain an emotional state based on this input and a measure of how well the UAV was achieving the goals. The state could be represented with measures of exploration, self-preservation, and the need for fuel, which could be thought of as paralleling the biological emotions of hunger, fear, and thirst.

The emotional state of the system would drive the importance of any motivation. For example, while searching for an object and sensing a down draft over a mountain, the emotions may attempt to raise the "avoid collisions with mountains" motivation to be higher than the "find object" motivation. That motivation may choose to turn back or choose another behavior based on the current motivation and the emotional state.

Although not developed as a behavioral model, the MIDAS project (Man-Machine Integration Design and Analysis System) [40] developed at NASA Ames used a similar paradigm to investigate the use of cognitive engineering and perceptual modeling to human machine issues in complex environments. Lessons learned from this successful program could be used to drive the development of a behavioral model for Autonomous UAVs.

A Lexicon of Behaviors

The terrestrial UAV demonstrator will be enhanced with additional hardware and sensors in order to implement and demonstrate the bio-inspired mission/flight control behaviors. This will require installation of a secondary processor (responding to stimulus) interfaced to the standard flight control computer/avionics. Most advanced behaviors will involve a response to (or the absence of) sensor stimulus. Behaviors currently assume returning to base. Some flights may be one way by necessity or choice.

Table 4. A Preliminary Lexicon of Aerial Explorer Flight Behaviors

Function	Function Description	Biological Model & Source	Potential Aerial Explorer Implementation
UAV "Primitive" Tasks:			
Basic			
Maintain Airspeed (Airspeed)	Maintain airspeed within parameters	MLB Bat	
Maintain Altitude (Alt)	Maintain altitude within parameters	MLB Bat	
Home to waypoint (relative waypoint)	Vehicle flies directly to the specified relative (x, y) waypoint	MLB Bat	
Fly route to waypoint. (from, x, y, to x, y)	Fly to and intercept route between the given waypoints	MLB Bat	
Advanced			
Fly route to 2D waypoint(latitude, longitude, altitude, and speed)	Fly to a specified x, y position and altitude	MLB Bat	
Autonomous takeoff (sequence of 2D waypoints)	Perform autonomous takeoff procedure flying through these 2D waypoints.	MLB Bat	
Autonomous Landing (sequence of 2D waypoints)	Perform autonomous landing procedure flying through these 2D waypoints.	MLB Bat	
Fly X pattern over ground waypoint(x, y,)	Fly a single crossing pattern over specified waypoint.	MLB Bat	
Fly ¼ mile circle relative to waypoint(waypoint, time)	Fly a ¼ mile circle around a waypoint for specified number of minutes.	MLB Bat	

Upload and execute sequence	Upload a new sequence of commands and execute them	MLB Bat	
Observations:			
Track(FEA...)	For example, circling over "Big Orange Tarp", for pod drop to up-link data		
Spot(FEA...)	For example, FEA= "Big Orange Tarp"		
Inspect(...)	Reduce altitude and speed and enable full bandwidth onboard data acquisition for SPOTted and/or TRACKed FEA features		
IRez(...)	Variable programmable digital imagery archive resolution		
Scan()	Periodically sweep onboard science camera pan and tilt to observe terrain off-axis of main heading		
Actions:			
RandomWalk(...)	Random two-dimensional way-point control; altitude is proscribed and constant	E. Coli Bacteria [1]	
RandomWalk(direction)	Random two-dimensional way-point control around some route or direction; altitude is proscribed and constant		
IRandomWalk(TDUR,TOL...)	Variant of RandomWalk(...) function wherein back tracking over territory that has been already explored is prohibited		
Dive()	Adjust wing configuration and power to allow rapid descent in altitude	Ducks, Cormorants	
FollowGrad(PARAM, ϕ,...)	For example, PARAM=SUN (for sun tracking) PARAM=ELEV (for terrain following to higher or lower elevation; PARAM=REFLECT (for following ground reflectivity to track polar icefields), PARAM= MOIST to use onboard air sampling probe to follow water humidity gradient; PARAM=GAS to follow certain atmospheric chemical constituent concentration gradient (such as sulfates for indication of volcanic activity); etc. ϕ= Flight heading relative to local gradient vector	E. Coli Bacteria [1]	
NGrad(PARAM1, PARAM2,..., W1, W2,...,...)	Multi-parameter, weighted version of FollowGrad(...);	Bees	For example, PARAM1=ELEV and PARAM2=MOIST, aircraft could fly to cliff-face using ELEV gradient but change heading if air probe senses increase in humidity measurement to find water outflow gullies along cliff face
Flitter()		dragonflies	Series of pre-programmed transient control inputs & maneuvers used to perform system identification, control health monitoring, and adaptive control tuning
FollowBoundary(PARAM,OFF...)	PARAM = same set as above; OFF= three-dimensional offset distance from PARAM boundary, or contour	Fox	If PARAM=ELEV, then could follow along chain of foothills or crater edge, for example.
Glide()	Reduce power to minimum and maintain wings level, descend at a slow vertical speed.	Birds	
PodDrop()	Release of drop pod for "ground truth"		
PopUp-Map()	Rapidly climb to high-altitude and perform panoramic survey/mapping of "over the horizon" surface features	Hawk, Vulture	
Drift()	Abandon all control in some axe(s).	Dandelion Seed	
Stationkeep	Remain over a position and collect data	Kite	
Skim()	Fly low within ground effect and sample ground material or gasses	Ocean birds	
Sting()	Release of ground-penetrating probe	Wasps	
SpeedAltPropGrad(MINALT,MAXALT,VMIN,VMAX,...)	Speed and altitude of aerial vehicle directly proportional to magnitude of PARAM gradient with pre-defined limits of altitude and speed		Aerial explorer flies high and fast when there is little or nothing to observe, and flies low and slow when something of interest is found
Soar()	Use thermals and updrafts to rise up and maintain altitude with minimum power.	Hawks, Vultures	
Swoop()	Descend to the ground in a parabolic arc, allowing measurements or ground samples to be taken at the low point	Birds of prey	
ZigZag()	Pre-programmed (or random within limits) deviations from main heading course to gain new perspective of terrain below aerial vehicle	Bees and dragonflies	
Terminus(OP,TPNR...)	OP = 0 (Return to starting point of flight and initiate remote-piloted landing); OP =1 (Return to starting point of flight and complete automated soft-landing); OP=2 ("Fire and forget," i.e., keep flying until aircraft falls of sky); OP=3 (intentional grounding/soft-crash landing of critical remote site of interest); etc; TPNR is the time of point of no return		"What goes up, must come down." And how an aerial flyer concludes its flight/mission will likely be equally important as any other flight/mission profile element.
Complex Behaviors & Mission Profile:			
Map(resource, area...)	Develop a map of a specified resource within a given area. Result includes a utility for that area. May include a frequency of appearance of resource.	Wolves	
Sales(...)	Traveling salesman solution, accounting for available aircraft resources and health, of SPOTted and MAPed features, FEA, to back track and enable CULL() function		
Cull(TNPR,...)	Given features SPOTted, and MAPed, during initial portion of flight (time<TNPR), then SALES executed and aircraft back tracks to do detailed low-altitude observation, INSPECT, or POD dropping	Lion	
Profile(...)	Defines/enables mission/flight profile; can be changed mid-flight		
RandomProfile(SUC,T...)	If FEA observation success, SUC, is low and flight time, T, is high, then		
Guess(...)	Through a combination of stochastic sampling		

	theory (FEA observations) and advanced extrapolation/interpolation algorithms of PARAM gradients a heuristic prediction would be made to continuously correct flight profile to maximize probability of search success		
Cooperative Behaviors			
Symbiosis(N,TYP1, TYP2,..., PROT1, PROT2,...)	N = number of active cooperative robotic systems in mission at time of flight; TYP1, TYP2, etc. = type of cooperative systems to be interfaced with; PROT1, PROT2, etc. = interface protocol for the various cooperative systems	Hummingbirds and Trees; dogs and humans	Examples: lander and aerial vehicle; rover and aerial vehicle: two aerial vehicles
Symbiote()			Release of micro-rovers and/or micro-scouts flyers from primary aerial explorer to enhance mission
Specialize (A1, activity; A2, activity2)	Through cooperation, specialize tasks temporarily to achieve goal	Birds defending, one draws attacker away, other protects nest	Upon finding a goal, with low fuel reserves, 2 aircraft cooperate to allow one to impact the site, while the other insures resultant readings are received.

7. CONTINUING WORK

The Road (Route) to Haughton Crater

There are many technical and operational challenges to autonomous UAV flights at Haughton Crater. The initial Haughton Crater field demonstration and site familiarization visit, as described earlier in this paper, encountered several operational issues. Lessons learned from these experiences include problems with batteries and difficulty starting glow engines due to the cold climate; lack of long, flat takeoff and landing areas due to the rocky and hilly terrain; frequent high winds and low ceilings; the need to protect the equipment from dust and water; and the need to work in cramped quarters due to the minimal lab and housing space available on site. These issues will be resolved through better pre-demonstration test-preparation.

There are several technical challenges at Haughton Crater that are known from experience with previous summer field seasons at the Mars-analog site. There have been a small number of previous aerial vehicle demonstrations at Haughton Crater. For example, Carnegie Mellon University operated an Autonomous Helicopter in this area in 1998 and first noted difficulty with GPS navigation [42]. The Micropilot aircraft flown this year also had difficulties with GPS when running with a new camera attached. Although handheld use of GPS at Haughton seems nominal, the difficulties with GPS encountered by these aircraft may be due to the coverage of the satellites in this extreme northern position or to interference generated by other systems and components on the aircraft. This challenge will be resolved by adequately shielding electronic components in the follow-on demonstration aircraft, and by adding dead-reckoning algorithms to the navigation system.

Most autonomous flights to this date have been in flat areas. Line of sight transmission of signals will likely be a challenge, as well as developing flight plans and paths that will avoid proximity to hills and allow autonomous transition to flight and landing. Flight control algorithms will be developed and tested in similar terrain near Ames Research Center, prior to the Haughton Crater Mars-analog demonstration.

Candidate Haughton Crater Scenarios

The following biologically-derived scenarios are under consideration for development and demonstration at Haughton Crater.

r & K Strategy Haughton Crater Experiment Mission Scenario

Deployment area and Hypothesis: A scientist familiar with the area chooses a general area of distribution based on a preliminary hypothesis that could be evaluated by the mission.

r- Pod Deployment: A fixed wing UAV is used to deploy a number of simple parachute-borne sensor pods within the area. The deployment of the pods is accomplished by flying randomly chosen routes and deployment positions from the departure point. Each pod would contain sensors that are capable of measuring and reporting science data (for example temperature, moisture, albido, microscopic images, etc.) and position (GPS or relative) after landing.

r-pod Data Return: The data from the pods is gathered and returned to the base station for evaluation. This is nominally be accomplished via broadcast and reception by a high-flying UAV or transmitted directly to the base station.

Data Analysis and K pod Deployment Planning: The r-strategy data is analyzed in order to recommend locations where the K strategy pod will be placed. The output of the analysis is a utility value (interest value to the scientists) for each pod position.

Using the utility values for each of the pod sites and an understanding of the performance limitations of the K-pod delivery system (nominally a rotorcraft), a planner determines the order of which site(s) can be efficiently and safely visited to take closer measurements. The K-pod includes a more sophisticated sensor package that may also include a sample return capability.

K Pod Deployment: Using the given plan, the K-pod UAV visits those sites of interest, positioning the K-Pod on the ground within a reasonable distance of the pod reporting the data. The UAV waits for the science experiments to be completed at that site then moves on to the other site(s), based on the state of the flight environment and the resources remaining. Alternatively, the UAV returns to the base, leaving the K-pod at the site to be returned at a later time.

K Pod Data Return: Data from the K-Pod is stored on board to be delivered upon return, or is transmitted via a communications link to base in real time. If the UAV did remain in communication with the base, modifying the deployment positions is possible

"Fox and Mouse" Strategy Haughton Crater Experiment Mission Scenario

Entry: The UAV is flown to an altitude of 3-5 times the nominal fight altitude over the test area. The UAV uses both an altitude and visual sensor to develop a rough estimate of the terrain (hills vs. plains). The UAV reduces its flight altitude to a nominal flight altitude over the plains area and begins a mapping task.

Map initial transition zone: The UAV searches for and finds an initial transition zone "swatch" between the plain and the rough terrain using the altitude sensor to measure the slope of the terrain. The width of the swatch (from plain to rough area) is defined within some range of slope. Once an initial transition is found, the UAV proceeds to map the slope of the area to either side of the transition swatch to some fixed distance in either direction.

Find indicating entry points within the transition zone: The UAV searches the mapped transition zone for water indicating terrain features (possible river beds, gulleys, specific rock features) at a lower altitude, allowing a finer resolution to the sensors.

Follow entry points to interesting features: The UAV chooses one of the entry points and follow that feature, using the multi-characteristic "slope" presented by features within the riverbed (albedo, rock type, etc.) looking for additional features indicating water.

Recognize and catalog characteristic features: When presented with interesting or unordinary features, the UAV recognizes and marks the positions of these items.

Finally, for illustrative purposes, a sample meta-code program for an aerial explorer Haughton Crater flight demonstration would look similar to the following:

Table 5. Flight Scenario Meta Code Example.

TakeOff()	*Manual RC take-off with manual switch-over to flight computer*
Scan()	*Periodically, throughout flight, do sideways imaging of the terrain below the aerial vehicle*
Spot(TARP,...)	*Continuous vision-system monitoring for PARAM=TARP, a series of large orange tarps placed by test team in the survey area*
IRez()	*Upon SPOTting a TARP increase resolution/size of digital image sizes for overflight*
Inspect()	*Upon SPOTting a TARP, reduce altitude and speed and perform close overflight of TARP*
Map()	*Map the TARP in terms of aerial vehicle relative coordinates; multiple TARPs may be identified and MAPped*
Profile(N,...)	*Flight computer initiates pre-programmed flight profile of N legs.*
PopUpMap(SPIRAL,RADIUS,ELEV,AZ,...)	*First flight profile leg initiated; UAV climbs in a spiral (vs straight climb) of a pre-set RADIUS to a maximum ELEVation and takes a panoramic image across a pre-set Azimuth*
DescendToAltitude()	*Reduce altitude to pre-defined cruise altitude*
IRandomWalk(TDUR,TOL,...)	*For a time period of TDUR, execute an intelligent (no back-tracking) random walk at cruise altitude; heading changes to be in minimum increments of TOL degrees*
NGrad(REFLECT, ELEV,0.25,0.75,...)	*Automatically switching from a random walk 'search and find" strategy to a two parameter follow the gradient strategy: proceed from highest to lowest elevation (accounts for water and organic debris flowing downstream) with highest weighting, and follow from lowest to highest reflectivity (assumes sediment and ice will have greater reflectivity than larger rocks left upstream) having lowest weighting; orange tarps will be placed by test team to be consistent with these follow the gradient assumptions*
Sales()	
Cull()	
Pod()	
Track()	
IRandomWalk(TDUR3,...)	
Terminus(0,TPNR...)	*With flight termination OP=0, then when time equal TPNR then aerial vehicle returns to flight starting point for manual landing*
Land()	*Manual switch-over upon visual contact from automated flight control to manual RC control*

8. CONCLUDING REMARKS

This paper has discussed an alternate bio-inspired approach to mission planning and execution for autonomous aerial vehicles. The particular emphasis placed in the paper is on aerial explorers for Mars missions. Further, the concepts outlined in the paper are applicable to a general class of aerial vehicles, and not particular aircraft or mission concepts.

The work outlined in the paper is in support of the NASA Ames 'BEES for Mars' project - a research effort focused on demonstrating the potential application of bio-inspired technologies to aerial vehicles and to the NASA planetary science program.

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